

Pandora's Box Opened Wide: UAVs Carrying Genetic Weapons

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CHAPTER 8

Pandora's Box Opened Wide: UAVs Carrying Genetic Weapons

Daryl J. Hauck

I. Introduction

With progressive battlefield success in Operations Desert Storm, Allied Force, Enduring Freedom, and Iraqi Freedom, unmanned aerial vehicles (UAVs) are capturing the imagination of militaries around the world. The specter of Iraqi UAVs with a 300+ mile range capability carrying chemical/biological weapons was described by U.S. Secretary of State Colin Powell in his February 2003 remarks to the U.N. Security Council.¹ A recent Rand report on chemical and biological weapons (CBW) identifies UAVs as a feasible CBW delivery means by potential adversaries like North Korea.² With significant concern regarding the ability to defend against a delivery vehicle several meters in size, imagine the difficulty in defending against a future scenario involving swarms of micro UAVs (MAVs) carrying genetic weapons with the potential to create powerful and precise political, economical, and military effects from a tiny payload. With a motivation towards avoiding technological surprise, this paper notes emerging trends in several technology areas that collectively point towards this possibility. In particular, biomimetics, micro electro-mechanical systems (MEMS), and nanotechnology offer great promise in enabling feasible micro UAVs (MAVs) as delivery platforms, while these same technologies along with genetic research may enable the packaging of powerful and precise weaponry (potentially target-specific) in a microscopic payload that could be carried by these MAVs. The MAV/genetic weapon combination may offer a capability with enough power, precision, discrimination, and military utility to challenge the notion of all biological weapons being considered weapons of mass destruction (WMD), thus widening their potential use.

At first glance, the premise above appears to border on fantasy, requiring the accomplishment of several miracles in diverse fields. After digging deeper, one finds that the basic science of key enabling technologies has already been invented. While not yet mature nor integrated on the scale envisioned in the opening premise, it's not unreasonable to predict this may happen within 20 years. The accelerating pace and dual-use nature of the relevant technologies coupled with the desire for an asymmetrical advantage over the U.S. may serve to advance such a threat. The probability of occurrence is at least minimal, and the

potential consequence of such a development is severe; therefore, this situation calls for a prudent mix of risk avoidance and mitigation measures. To ignore this possibility fails to learn the lessons of history. In 1945 Admiral Leahy advised President Truman "...The [atomic] bomb will never go off, and I will speak as an expert in explosives."³ Circa 1949, acclaimed mathematician and computer science pioneer Dr. John von Neumann stated "it would appear that we have reached the limits of what it is possible to achieve with computer technology, although one should be careful with such statements, as they tend to sound pretty silly in 5 years."⁴ A failure to account for the possibility of MAVs carrying genetic weapons and to respond in a meaningful way may result in a technological surprise that could add substantially to the cost in lives and/or resources required to achieve a strategic objective, and ultimately may play a key role in the ultimate outcome of a future contest. The goal is to avoid the fate of the French at the Battle of Crecy in 1346, where the English introduction of the longbow kept a numerically superior French force from penetrating English lines during sixteen cavalry charges, the first time in a thousand years that an infantry force defeated a numerically superior cavalry force, which ultimately led to the British capture of Calais and England's advancement to international power status.⁵

This paper begins with a discussion of general technological themes and the law of unintended consequences...themes that are continually reinforced as specific enabling technologies are encountered throughout the essay. Subsequent sections build on this foundation by investigating several technology challenges specific to the hypothetical threat system, MAVs carrying genetic weapons. Sections two and three more specifically address technology challenges and enablers for the air vehicle and payloads. The paper concludes with a discussion of existing or potential responses and offers recommendations on technologies and information the U.S. should seek to ban, delay or control.

General Technology Themes

While science concerns itself with discovery, technology focuses on the application of scientific knowledge to solve specific problems. Physicist and futurist Michio Kaku predicts that the weight of creative progress in this century will lie more in inventions involving interdisciplinary synergies than it will in new discoveries within specific scientific disciplines.⁶ An insightful example with specific relevance to this paper involves the mapping of the human genome. Due to the sheer

computational complexity and measurement expense, biologists tended to believe that the human genome could not be mapped within a reasonable budget or time horizon. Involvement by computer scientists, advances in computational power, and cost reduction in type-matching processes enabled project completion in 2003, well in advance of anyone's predictions. The cost of gene sequencing dropped from ten dollars per base pair in 1990 to fifty cents per base pair by 1997.⁷ This is but one example of the impact of inter-disciplinary approaches...this theme continues to be prevalent in remaining chapters.

The importance of intra-disciplinary innovation supports inventor Ray Kurzweil's theories involving his "law of accelerating returns." Kurzweil noted that Moore's Law on integrated circuits (capacity and speed double every twenty-four months) applied not only to integrated circuits but to computing technology in general throughout the 20th century.⁸ Through the progression of mechanical devices, relay-based computers, vacuum-tube computers, discrete transistors, and now integrated circuits, this rate of progress was continually realized...it "simply" took an innovation from another technology applied to the problem of computation. While many project Moore's Law to exhaust itself by 2020, Kurzweil notes that may be true with respect to integrated circuits but instead predicts that exponential computing growth will then press ahead, based on some other technology, as it has for five technology generations.⁹ Similarly, Kaku observes that DNA sequencing speed doubles roughly every two years.¹⁰

"Accelerating returns" alone may not be sufficient for desired breakthroughs. Complexity theory demonstrates that exponential growth in computational power does not translate into exponential growth in problem solving capability. Furthermore, physical phenomena may approach true boundaries. As they get smaller, micro UAVs based on fixed-wing technology appear to be reaching aerodynamic limits—the forces at this scale are compared to a "human swimming in honey."¹¹ In this instance, however, Kaku's prediction that cross-discipline approaches are likely to bring solutions may be operative. The second section contains an example of researchers looking to insect flight for answers on small-scale aerodynamic forces. The discussion of these trends is more than academically interesting. It tells us that we can and should expect others to look for multi-disciplinary approaches to improving UAV technology, and that advancements may come faster than anticipated.

Law of Unintended Consequences

Simply stated, this law highlights that the “actions of people...always have effects that are unanticipated and/or unintended.”¹² This law may operate in several important ways to bring about the hypothetical threat system. The primary mechanism is the dual-use nature of the technology involved. In gaining the knowledge to cure/repair disease, one also gains the knowledge on how to create and spread it. As one reduces the cost to produce a therapy, one also reduces the cost to produce a potential weapon. Leaders in genetic research may find themselves under considerable moral pressure to share information rather than restrict its flow to what they alone can pursue within their own resources. The information presented in subsequent sections shows that the technology required to bring about the envisioned threat system has and will continue to rapidly progress largely on its own merits for peaceful purposes, thus reducing the number of “miracles” required.

A second mechanism is the attempts by First World nations to limit weapons of mass destruction proliferation to other countries and non-state actors, which may drive nations to seek other asymmetrical responses, refuse to sign new conventions, and/or withdraw from existing conventions. The U.S. may have unintentionally created a “precedent” with respect to the Anti-Ballistic Missile treaty, the International Criminal Court, and the Kyoto environmental protocols.¹³ With the aforementioned themes generally establishing the motivation and ability to realize the hypothetical threat system, the following two sections more specifically address technology challenges and enablers for the air vehicle and payloads.

II. Air Vehicle Challenges

Micro UAVs (MAVs) are already a reality (Figure 8.1).¹⁴ The Wasp, for example, has a 13- inch wingspan (flying wing), weighs six ounces, is propeller driven via electric motor with a lithium-ion battery, and is radio controlled.¹⁵ Although micro UAVs clearly exist, they are difficult to make with a sufficient payload and range within tight size/weight/power constraints. Less obvious are the challenges of aerodynamics on this scale. As wing size gets smaller and flight speeds get slower, drag gets large and lift gets small—conventional aerodynamics (airflow over curved wings) would predict that insects cannot fly.¹⁶ To deal with this challenge, some researchers turn to nature for clues.

Biomimetics and Aerodynamic Forces

Biomimetics studies biological mechanisms for sensing, control, and propulsion¹⁷ with an eye towards implementing those functions in an electro-mechanical device, potentially including integration of biological materials with those devices.¹⁸ The airplane began as a biomimetics experiment. The Wright Brothers used wing warping to assist in stability and control of the Wright Flyer—an idea that inspired Wilbur after he watched pigeons rotate their wings indepen-



Figure 8.1 Micro UAVs¹⁹

dently through positive and negative angles of attack.²⁰ To deal with the inability of conventional steady-state aerodynamics to explain micro-scale lift forces, researchers today are investigating insect flight. The following abstract summarizes the progress made by Oxford University researchers investigating butterfly flight:

...we trained red admiral butterflies...to fly freely to and from artificial flowers in a wind tunnel, and used high-resolution, smoke-flow visualizations to obtain qualitative,

high-speed digital images of the air flow around their wings. The images show that free-flying butterflies use a variety of unconventional aerodynamic mechanisms to generate force: wake capture, two different types of leading-edge vortex, active and inactive upstrokes, in addition to the use of rotational mechanisms and the Weis-Fogh ‘clap-and-fling’ mechanism. Free-flying butterflies often used different aerodynamic mechanisms on successive strokes. There seems to be no one ‘key’ to insect flight, instead insects rely on a wide array of aerodynamic measures to take off, manoeuvre, maintain steady flight, and for landing.²¹

Under a \$2.5M grant from the Defense Advanced Research Project Agency (DARPA) and the Office of Naval Research, researchers at the University of California at Berkeley have established the mechanical flying insect (MFI) project. The intent is to be able to mimic the “airborne prowess” of the fruit fly, noting its ability to swerve into turns that would rip apart aircraft, its ability to fly with a large part of a wing missing, and its ability to navigate with other sensors if blinded.²² Figure 8.2 shows a prototype MFI that flaps its wings at 204 times per second with sufficient force (500 μ N per wing) “for a 100mg machine to lift itself off the ground.”²³

Professor of integrative biology Dr. Michael Dickinson “discovered the last of three key ingredients necessary to make a fly fly...these wing motions are delayed stall...wing rotation...and wake capture...”²⁴ In “delayed stall,” the wing stroke uses a high angle of attack “that generates a large leading edge vortex, a large swirling vortex on the top surface of the wing that generates a very low pressure and consequently pulls the wing upward.”²⁵ The “backspin” involved in wing rotation “pulls air over the top faster than the bottom and as a consequence higher velocity means lower pressure...and effectively the wing is being sucked upwards as it rotates.”²⁶ In “wake capture,” an insect “flaps its wings back and forth [instead of up and down]

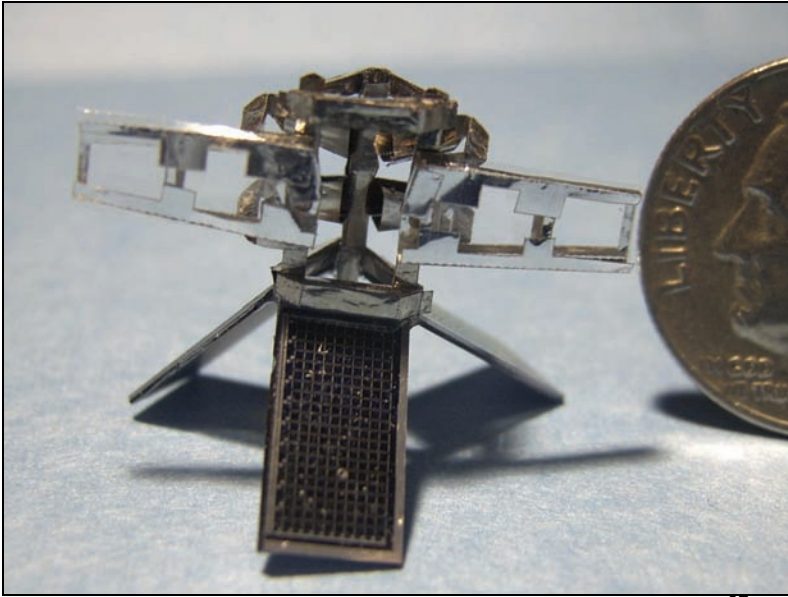


Figure 8.2 UC Berkeley Mechanical Flying Insect²⁷

and as a consequence the wing is always passing through the wake of a previous stroke and it's able to actually extract energy from the wake and this makes the wing beat rather efficient..."²⁸ The forces from "wing rotation" and "wake capture" accounted for the majority of additional lift that was not predicted or explained by conventional aerodynamics theories.²⁹

The MFI's wing-drive consists of a "thorax composed of thin sheets of stainless steel that, when cut and folded into "beams" [under microscope], turn out be extremely strong. Two hinged beams are attached as struts to each wing, with a piezoelectric motor driving them. When they move together, the wing flaps; when they move out of sync, the wing rotates."³⁰ The wings [not shown in the picture as they are removed from the "ladder-like" horizontal structures] are "about half an inch long, 1/20 the thickness of a sheet of paper and made of lightweight polyester, look like miniature paddles, and give the fly a wingspan of about one inch."³¹

The Berkeley MFI research team and laboratory is noteworthy from a couple of perspectives. Whereas the Oxford butterfly research contributed to the theory of insect flight from "smoke-flow visualization," the Berkeley research used "dynamic scaling," building large insect wings to flap slowly in a two-ton tank of high viscosity mineral oil.³² This allows for scaled measurement and modeling of forces not possible via smoke-flow visualization. Having accomplished this measurement and

modeling for a stationary hover, the Berkeley research is moving on to a larger tank to translate the flapping device through the fluid to model aerodynamic forces “in flight.”³³

In addition to studying aerodynamic forces, the Berkeley team is able to study insect “flight control” by tethering a fly inside a chamber upon which shapes and colors are projected to study the insect’s flight control response to visual cues.³⁴ The multidisciplinary nature of the Berkeley team, “a whole variety of engineers—mechanical, electrical, computer and materials scientists—all taking inspiration from our biology colleagues,”³⁵ is largely responsible for their rapid accomplishments to date and is predictive of eventual success. The team’s goals include: MFI “lift-off” in 2004; autonomous indoor flight with integrated battery, sensors, and electronics in 2006; and commercial availability by 2012 for applications in search and rescue, building surveillance/security, targeted pesticide application in agriculture, and entertainment.³⁶

Another promising biomimetic technology involves ionic polymer-metal composites (IPMCs) as biometric sensor actuators and artificial muscles.³⁷ Shahinpoor *et al.* report that strips of these composites undergo large bending and flapping displacement if an electric field is imposed across their thickness, making them large motion actuators. Conversely, when bent by some other force (such as a gust), voltage is produced across the strip making it a large motion sensor. They further report these composite “muscles” have been shown to work well in harsh cryogenic environments (a few Torrs and -140 degrees Celsius). Figure 8.3 shows commercial versions of this material available from Biomimetics, Inc. in the form of MuscleSheet™.³⁸



Figure 8.3 “MuscleSheet”³⁹

The Musclesheet™ can operate in the 0.1 to 3.5 volt range, can generate forces 10-50 times its weight (voltage/size dependent), can bend “100% of effective length up to ± 90 degrees,” and varies in thickness from 0.008-0.020 inches.⁴⁰ The advertised cycling rate is 100 Hz “size/weight dependent,” which is substantially below the 204 Hz achieved in the MFI’s piezoelectric motor driven approach, so it may be more appropriate for crawling or swimming devices. Even so, the future potential of similar technologies should not be discounted, as scientists at the University of British Columbia are specifically investigating the potential for electro-active polymers to power a mechanical dragonfly. The materials they are working with can expand to twice their original length, while biological muscles such as the human bicep contract by only twenty percent.⁴¹

Biomemetics and Flight Control

In addition to lift/thrust generation, biomimetics offers several approaches to addressing flight control issues. Wu *et al.* describe three types of biomimetic sensors to aid in flight control

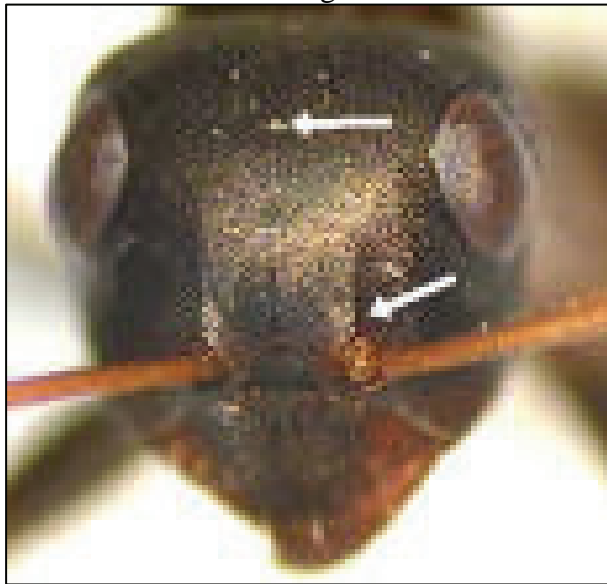


Figure 8.4 Ocelli⁴²

of the Berkeley mechanical flying insect.⁴³ An insect’s ocelli (Figure 8.4), photoreceptors that collect light from different regions in the sky to help an insect maintain horizontal stabilization and avoid obstacles, are mimicked with four photodiodes and accompanying control logic to detect changes in light intensity. Halteres (Figure 8.5), small balls at the end of

thin sticks that beat anti-phase to the wings at wingbeat frequency in order to detect rotations around all three turning axes, are mimicked with tiny beams and strain gauges that form piezo-actuated vibrating structures. Optical flow sensors consisting of linear arrays of elementary motion detectors mimic optomotor responses whereby insects tend to turn in the direction of an optical stimulus in order to reduce image motion on its “eyes.” A MEMS compass that uses three metal loops to detect changes in the earth’s magnetic field is added to the biomimetic flight control suite to provide heading control.

Micro Electro-Mechanical Systems (MEMS) and Flight Control

MEMS technology facilitates the extreme systems integration required for micro UAVs. As an example, the automotive industry integrated accelerometers and electronics for airbag deployment on a single silicon chip while reducing costs by an order of magnitude (\$50 for a discrete component system reduced to \$5 per automobile using MEMS).⁴⁴ Draper labs has developed MEMS gyroscope technology (see Figure 8.6) and licensed it to Rockwell, Boeing, Honeywell, and others.⁴⁵ Their tuning fork gyro contains a pair of masses that vibrate out of plane when rotated, with the out of plane motion sensed capacitively.⁴⁶ Samsung Corp has implemented gyro stabilization of camcorders for as little as \$10 per sensed axis.⁴⁷ Analog Devices, Inc. offers a MEMS gyroscope (Figure 8.7) in an ultra small and light package, less than 0.15 cubic centimeters and less than 0.5 grams.⁴⁸ MEMS technology allows integration of navigation and stability control system in the same chip/package as the MAV’s computational/control logic.





Figure 8.5 Halteres⁴⁹

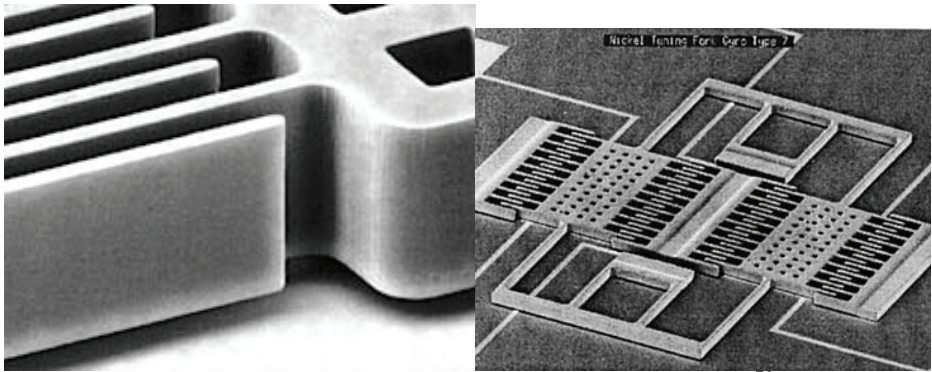


Figure 8.6 Draper Labs Tuning Fork Gyro⁵⁰

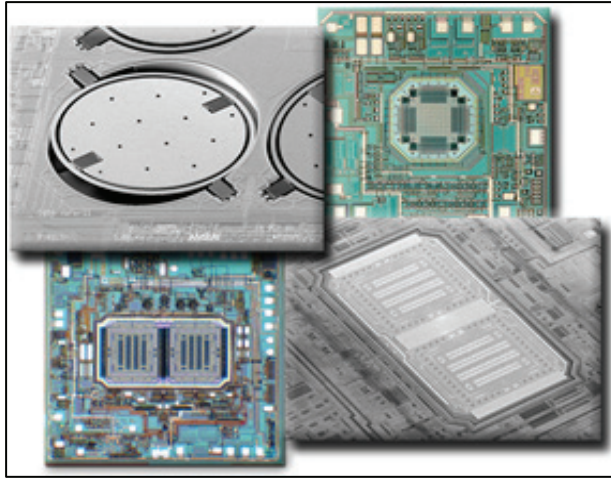


Figure 8.7 ADXRS150 Angular Rate Sensor⁵¹

Recent advancements were made possible by the use of lithography processes prevalent in semiconductor manufacturing, which build up the parts in layers at their final position, thus overcoming the problems inherent in assembly on such a small scale. Figure 8.8 is an electron microscope view of a prototype gear and chain drive mechanism built using these techniques. Use of semiconductor lithography techniques requires significant initial investment in design, mask preparation, and process tuning to achieve suitable yield rates but enables low cost production at large quantities—a model well-suited to building swarms of MAVs. The Berkeley and British Columbia teams have material cost goals of a dollar or less per mechanical insect.⁵²

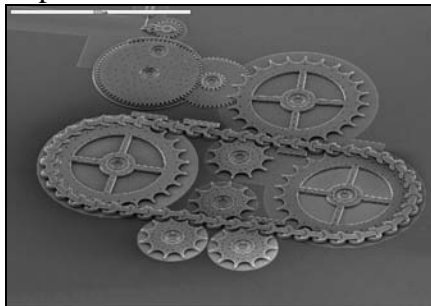


Figure 8.8 MEMS Gear and Chain Drive⁵³

Nanotechnology

Nanotechnology's promise includes: “essentially every atom in the right place; make almost any structure consistent with the laws of physics

that we can specify in molecular detail; [and] have manufacturing cost not greatly exceeding the cost of the required raw materials and energy.”⁵⁴ The very idea of nanotechnology has been around at least since 1959 when physicist Richard Feynman posited the question of arranging atoms “one by one the way we want them.”⁵⁵ Today, the nanotechnology concept is being popularized as “molecular manufacturing.”⁵⁶

In a general sense, nanotechnology can facilitate the extreme systems integration required for increasingly smaller micro UAVs...to achieve on an even smaller scale what MEMS has already accomplished. A specific example would be the potential to integrate structure with power and control conductive paths using carbon nanotubes to replace conventional wiring (Figure 8.9).⁵⁷ Researchers at the University of Texas at Dallas have manufactured fibers from nanotubes that are “four times tougher than spider silk and 17 times tougher than the Kevlar used to make bulletproof vests.”⁵⁸ The Technion-Israel Institute of Technology has demonstrated using DNA, metal particles, and carbon nanotubes to self-assemble a nanotube transistor.⁵⁹ Additional nanotube applications include antennae, batteries, and electromagnetic shields.⁶⁰

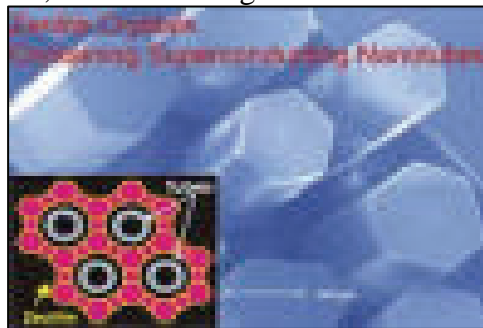


Figure 8.9 Carbon Nanotubes⁶¹
Air Vehicle Conclusions

The previous account illustrates the existence of several enabling technologies that are being applied to the challenges of MAV propulsion and flight control. Given the Berkeley MFI’s “technology push” accomplishments to date, the presence of several critical enabling technologies, and the accelerating nature of technology trends in general, the Berkeley team’s goal of a commercially available system by 2012 does not seem unreasonable. A mechanical insect based approach over a fixed wing approach is not farfetched. Experiments show that insect power efficiencies are five times greater than fixed wing aircraft.⁶²

There is also a “requirements pull” aspect motivating the creation of operationally viable MAVs, much of which is summarized nicely by

Huber.⁶³ Additionally, “with 70% of the world’s population living in urban environments, future conflict is likely to be primarily urban,”⁶⁴ as the nation building stage of Operation Iraqi Freedom vividly demonstrates. Furthermore, “the lack of ‘round-the-corner’ intelligence removes much of the advantage of Western military technology.”⁶⁵ MAV-based reconnaissance could do much to service this gap.

These technology push and requirements pull aspects lend a sense of inevitability to the attainment of MAVs on a scale approaching one inch. A potential unintended consequence is that the pursuit of a commercially available product provides the delivery vehicle portion of one hypothetical threat system, MAVs carrying genetic weapons.

III. Payload Challenges

With much of a MAV’s weight and volume dedicated to propulsion, structure, and flight control, carrying a meaningful sensor or weapons payload is a challenge. MAV literature tends to focus on sensing payloads. This section discusses payload-enabling technologies stemming from biomimetics, MEMS, nanotechnology, and genetic research.

Biomimetics and Sensing

The “Black Widow” in Figure 1 carries an off-the-shelf color camera chip with a resolution of 510 x 492 pixels.⁶⁶ Carrying an infrared or radar sensor would be especially challenging, given the former’s need for additional weight/space/power for a cooling system and the latter’s need for substantial power and longer antenna length for angular resolution. Biomimetics offers some opportunities in the sensing arena. Realizing that “if nature can produce enzymes, receptors and antibodies by evolution, then molecular engineers should be able to develop materials with similar properties by design,” hundreds of research centers and companies in the U.S., Europe, Japan, China, and Russia are pursuing new generations of stable biomimetic sensors.⁶⁷ As an example, the U.S. Air Force Research Lab Materials Directorate has developed a biomimetic thermal imaging sensor by embedding heat-radiant sensitive biological material in a capacitive polymer substrate.⁶⁸ When pointed at a heat source, the biological material changes the capacitance of the polymer substrate resulting in a detectable signal. A brassboard has been constructed that consists of a 9x9 array with a manufacturing cost of less than one hundred dollars, an order of magnitude less than comparable IR sensors that rely on cooled sensor heads. The biomimetic sensor works at

ambient temperatures, avoiding the weight/space/power penalty of carrying a cooling system. The lab presently predicts a five-year shelf life of the embedded chemicals. Whether this technology progresses sufficiently to rival the performance of semi-conductor based bolometers remains to be seen. The Belgium-based corporation XenIC offers thermal detection elements embedded in integrated circuits;⁶⁹ and researchers at Delft University, The Netherlands, have demonstrated microbolometers at $3 \times 3 \mu\text{m}$.⁷⁰ The existence of competing technologies increases the potential availability of MAV-suitable sensors.

Heat sensing on the envisioned threat MAV may not need to be as high-resolution as we have become accustomed to with conventional IR sensors. In a swarm delivery mode, it may be enough to sense heat in a particular range, land on the object, check for a DNA match, and then deploy the genetic weapon. Directly deploying the genetic weapon may be sufficient if it doesn't matter who gets it as long as the intended target eventually does. This concept will be described more fully in the genetic weapons section later in the paper.

Genetic Research, Nanotechnology, and Target Detection

The Human Genome Project led by the National Institutes of Health is "one of the most ambitious projects in medical history, a \$3 billion crash program to locate all genes [100,000 genes in 23 chromosomes] within the human body by 2005."⁷¹ Over a decade, "gene hunting has accelerated by a factor of several thousand times with the introduction of computers, robotic laboratories, and neural networks,"⁷² resulting in actual mapping completion in 2003.

Previous DNA sequencing technology, Polymerase Chain Reaction (PCR), used to take days using fixed laboratory equipment.⁷³ Researchers at Northwestern University invented a handheld electrical detection technique that "can spot the DNA of nasty diseases in minutes instead of days" and is "ten times as sensitive and 100,000 times as selective as was PCR."⁷⁴

Regarding sensitivity, the device only requires "very few molecules to spot disease DNA;" and can "easily differentiate DNA associated with anthrax from DNA that's very similar but associated with something benign" (selectivity).⁷⁵ Nanosphere, Inc. has licensed this technology, is selling a benchtop version of the device, and is prototyping a handheld version.⁷⁶ NASA Ames is taking this further by developing a silicon chip with arrays of carbon nanotubes:

Prototypes consist of arrays of 2- to 200-square micron chromium electrodes on a silicon wafer. Multi-walled nanotubes ranging from 30 to 50 nanometers in diameter—about two orders of magnitude smaller than a red blood cell—cover the electrodes and are encased in a layer of silicon oxide. The nanotubes are packed onto the electrodes at densities of anywhere from 100 million to 3 billion nanotubes per square centimeter. The bottoms of the nanotubes are in contact with the electrode and their tops are exposed at the surface of the silicon oxide layer. Strands of probe DNA are attached to the ends of the nanotubes. When a liquid sample containing target DNA molecules comes into contact with the detector, the target DNA attaches to the probe DNA, and this increases the flow of electrons through the nanotubes to the electrode...the device is sensitive enough to detect DNA in samples containing as few as 3.5 million molecules...a drop of water contains trillions of water molecules.⁷⁷

NASA Ames is projecting availability for practical applications by 2005. While the intent of this research is to improve the speed and portability of medical assessments, the unintended consequence of the latter nanotechnology-based product could be that it provides a MAV with a sensitive and discriminating means of target recognition. As the electrical detection method requires a probe sample for matching, weaponeering would require a targeting database.

Targeting Databases

As this paper envisions a threat to the U.S., this section focuses on DNA registration activities that may make us vulnerable. The most obvious one is the blood samples that every military member submits for potential DNA matching in remains recovery operations. Electronic cataloging of this information, while seemingly useful to speed recovery operations (instead of having to locate original sample cards or paper records), would present a lucrative hacking opportunity for the genetic weaponeer. A second military-specific concern would be whether we are creating unique group signatures of military personnel by vaccination programs that are specific to the military (either with respect to a single vaccination not easily available to the general public such as the anthrax vaccine, or with respect to extensive combinations of vaccines given to

world-wide deployable personnel that would not otherwise be given by default to the civilian population).

Moving to the more general U.S. population (but still specific to a U.S. target database), there are at least two additional potential targeting databases. Noting the profound effect of DNA testing in law enforcement, President Clinton's 1994 Crime Control Act contained a provision for a national DNA data bank.⁷⁸ Understanding the need to preserve genetic diversity in crops, the U.S. maintains germ-plasma banks in a cooperative federal-state program.⁷⁹ More general to anyone is a desire to know health risk or family histories. Kaku predicts that everyone may have his own DNA sequence on a compact disc by 2020.⁸⁰ By mailing \$330 and a saliva swab to Britain's "Roots for Real," a person may have their mitochondrial DNA analyzed to determine a family continent of origin and potentially (for some customers) a town of origin.⁸¹ Three hundred and thirty customers have already signed up...who will control this database?

In every instance, the motivation for establishing these databases served a useful and peaceful purpose. A potential unintended consequence is that they provide a genetic targeting database of U.S. military personnel, private citizens, and crops. Leaving the protection of this information to the healthcare industry may be insufficient. A 2002 theft of computer equipment from the Phoenix regional Tricare office compromised medical information of thousands of military members and dependents. Information attacks may be attempted to ferret this information if attached to networks. While preceding sections focused on sensing and target detection, more problematic is the delivery of a militarily useful weapon in such a small vehicle.

MEMS Weapons Delivery

Delivering microscopic weapons off of the MAV, and getting those weapons into the bloodstream and into cells, is potentially understated as challenging. Adding levers and/or needles to the MEMS devices pictured in Figure 8 could potentially create an injection mechanism for weapons delivery. Devices such as Sandia Laboratory's Microteeth (Figure 8.10)

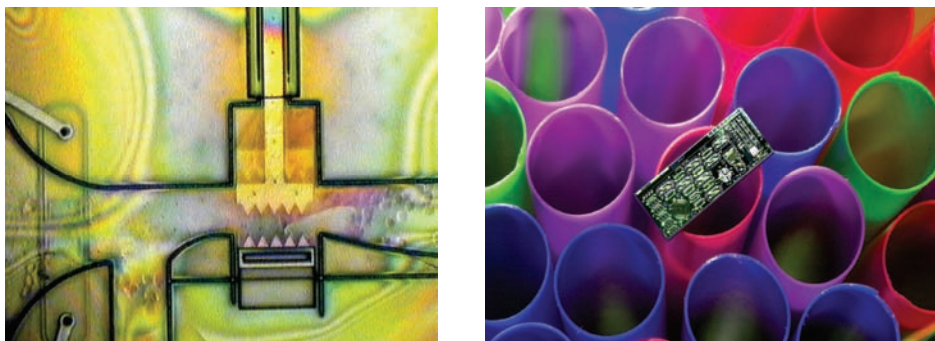


Figure 8.10 Sandia Laboratory’s “Microteeth.”⁸²

have been created to manipulate blood cells.⁸³ The left panel shows a microteeth device less than the width of a human hair handling a blood cell. The right panel shows multiple microteeth devices stacked five-across the width of a narrow chip that would fit inside of a straw. Single microteeth-like devices could fit well within a blood vessel to carry and insert genetic material into cells. Alternatively, the teeth could be used to puncture cells passing through or instead push outwards to latch onto vessel walls forming blockages and strokes.

A complementary delivery technology involves microneedles developed at the Georgia Institute of Technology. Researchers there have “developed ways to manufacture solid and hollow metal, silicon, plastic and glass microneedles that range in size from one millimeter to one thousandth of a millimeter.”⁸⁴ An array of 400 microneedles can be used to pierce skin, and such a micro array successfully delivered insulin to diabetic laboratory rats.⁸⁵ An eventual goal is to use these microneedles to “deliver microliter quantities of drugs to very specific locations.”⁸⁶ Devices based on this technology are anticipated to be on the market as early as 2008.⁸⁷

Genetic Weapons⁸⁸

While it is difficult to envision conventional weaponry achieving meaningful effects in this small payload scale, chemical and biological weapons delivered by MAVs may represent an attractive asymmetric capability to governments and groups that do not feel bound by international treaties governing their development, production, and use. The world observed the effect of small amounts of anthrax contaminating East Coast postal service centers and closing the Hart Senate Office Building. Historical reasons for banning these classes of weapons have

been that they are indiscriminate, difficult to control with unintended effects, may cause disproportionate civilian casualties for their military effect, and therefore do not possess military utility. Delivery of a small, powerful, precise kill mechanism potentially changes the paradigm.

An injector-equipped MAV with effective sensing may change the nature of this equation. Sandia Laboratory has demonstrated a microscopic machine that uses gears to deploy a probe that engages another adjacent microscopic machine. It is not much of a stretch to conclude that small toxin injectors could be created with similar technology and carried aboard a MAV. Hypothetically, a robust injector could also penetrate chemical/biological protective suits that would otherwise filter agents that relied on atmospheric propagation or contagion.

Biotech identification or discriminately effective weapons allow a brute force solution to challenges of UAV autonomy and communications links. If an injector is deployed with proper on-board identification, or the genetic weapon is effective only against an intended target, then the notion that a UAV must search for only its intended target (and communicate with a network-centric ISR constellation in order to do so) is no longer mandated. Swarms of mass-produced MAVs could be delivered to the approximate target area in a parasitic mode, then rely on modest propulsion and heat sensing to deliver the genetic weapon payload to any target encountered. The effect of precision targeting could still be achieved by a target-specific genetic weapon or a selective (DNA sensing) injector.

Several scientists describe the plausibility of target or class-specific genetic weapons. The director for research at the Institute for Genomic Research, Dr. William Nierman, projects one possible concept: "Load a common virus with a destructive gene, then release the bug into the

wild. Designed to activate only in the presence of a single host, the pathogen could flit unnoticed through an entire city of unwitting carriers, a "harmless propagation"...before reaching its target."⁸⁹ Dr. George Church, director of the Lipper Center, presents a scenario involving a "pathogen that targeted people with shared lifestyle traits."⁹⁰ While discussed in the context of genetically modified organisms intended to activate in the presence of STDs, illegal drugs, or even prescription drugs (RU-486 abortionists), there appears to be significant potential for class-specific targeting.

Other effects besides targeting individuals and groups of people are possible as well.

Dr. Mark Wheelis, a microbial biochemist and geneticist at the University of California-Davis, sees anti-agricultural bioweapons as within the reach of states, corporations, organized crime, terrorist groups, and individuals.⁹¹ According to Dr. Wheelis:

Since plant varieties are particularly inbred, and many domestic animals are very highly inbred, although not to the extent that many plants are, this does mean that, unlike humans, where there is a tremendous heterogeneity in any population, there's a very high degree of genetic homogeneity. So you can travel for a hundred miles in the Midwest and see thousands of square miles planted with exactly the same variety of maize. And that means, using what one knows of the maize genome, and of this particular variety of maize, it might be possible to develop a chemical agent that will affect one variety of maize, but not another....And so this does raise the theoretical possibility that one could tailor chemical or biological weapons to attack varieties of domestic crops or animals that were used in certain parts of the world and yet these chemicals or infectious agents would be harmless or much less harmful to other varieties.⁹²

Ramares notes the potential economic impact of such an attack by comparing it to a 2001 outbreak of foot and mouth disease in England during which 5.7 million animals were slaughtered at a cost of \$2.7 billion pounds over nine months. Given that the Human Genome has now been completely mapped, it is not inconceivable that researchers will begin to understand the effects of sequence changes and other code modifications during the next 10-20 years, especially factoring in technology acceleration trends discussed earlier in this paper. There are several specific research thrusts already on such a path, ostensibly intended for advancing medical treatment.

Corporations such as Genentech and AmGen have formed multidisciplinary research teams to advance genomic research for new medical therapies. Genentech now markets 12 protein-based products for serious or life-threatening medical conditions. They have created a bioinformatics department consisting of "professionals who possess an in-depth understanding of molecular biology and are skilled in computational methods for mining genomic data and software engineering."⁹³ They have also made substantial investments in "critical and innovative biochemical

and cell-based assay technologies that are fundamental for the discovery and characterization of potential therapeutic molecules.”⁹⁴ Two research thrusts of particular interest to this paper include Genentech’s investigation of apoptosis, the mechanism by which cells self-destruct, and of human epidermal growth factor receptor (HER) pathways, the signal process “by which cells are given their instructions to divide, survive, die, or differentiate (i.e., turn into something else).”⁹⁵ Apoptosis is:

...the mechanism by which cells self-destruct. This natural regulatory program for suicide exists in all cells, including cancer cells, and may prove extremely valuable in fighting the disease. Under normal conditions, apoptosis serves to eliminate damaged or unneeded cells from the organism. However, in cancer cells, this self-regulation program is silenced, allowing tumors to survive and grow.⁹⁶

Researchers at the University of Pennsylvania have isolated two proteins, Bax and Bak, that are involved in disrupting mitochondria to trigger apoptosis.⁹⁷ Overexpression of the HER2 gene is involved in 25 to 30 percent of breast cancer patients—Genentech’s Herceptin® was developed as a therapeutic antibody targeted to this cell surface protein.⁹⁸ An unintended consequence of this cancer research is that gaining an understanding of how to correct the regulation of these processes may also provide the knowledge to interrupt these processes so that damaged or unneeded cells are allowed to uncontrollably replicate, or that healthy cells are instructed to die—both potential forms of genetic weapons.

A genetic weapon would also require a means to insert itself into the target’s genetic code—a process referred to as gene transfer.⁹⁹ Present methods that study gene therapy in clinical trials involve the modification of viruses to remove disease-causing agents and insert the gene to be transferred, then take advantage of the virus’s biology to deliver the gene to human cells.¹⁰⁰ This method carries risks such as toxicity, immune and inflammatory responses, and gene control and targeting issues.¹⁰¹ To mitigate these risks, researchers are experimenting with directly introducing DNA into human cells via human artificial chromosomes (HAC). Because of their construction, the body’s immune system would not reject them.¹⁰² A potential unintended consequence is that the use of HACs in genetic weapons may render the body’s immune system defenseless against such weapons.

Payload Summary

Significant progress has been made in DNA detection and genetic research to enable improved medical diagnosis and treatment methods. A potential unintended consequence of this research is that it may provide the means to create the target detection, weapons delivery, and genetic weapons components of the projected threat system. The 15-20 year timeline projected in this paper is reasonable. A 1999 report by the British Medical Association predicted the arrival of genetic ethnic-cleansing weapons within five or ten years.¹⁰³ Left unchecked, allowing another 10-15 years for proliferation and integration with MAV delivery methods presents this potential weapons system arriving within our existing planning horizon. It is important to emphasize that rogue genetic weapons designers unconcerned with undesirable side effects are not constrained by typical medical research schedule drivers such as establishing and following extensive research protocols and receiving FDA approval to market. Even with this assessment, trying to accurately forecast the arrival of this hypothetical threat is not the crux of issue. Instead, it is important to understand the unintended potential of these efforts and take direct steps to prevent, delay, and mitigate negative outcomes. Even partial progress in the described technology areas may become militarily significant.

IV. Responses

If one agrees with the premise that MAVs with genetic weapons represent a paradigm-changing construct of military power, the next question becomes how to prevent or delay their onset. The first step is to evaluate current counter-proliferation and defense conventions, theories, and capabilities. This section discusses the applicability of legal conventions and deterrence theory, the difficulty with non-proliferation, and defense/consequence management.

Applicability of Existing Legal Conventions

The 1972 Biological and Toxic Weapons Convention (BWC) is the current cornerstone of non-proliferation; the Missile Technology Control Regime (MTCR) and self-defense doctrines also lend insight as to whether the hypothetical threat system is banned by existing legal conventions. The first relevant convention was the Geneva Protocol of 1925 that prohibited the *use* of both poison gas and bacteriological methods in

warfare following extensive use of poison gas in World War I.¹⁰⁴ By the late 1960s, a desire to separate treatment of chemical and biological weapons was favored in order to make faster progress on eliminating existing stockpiles and stopping further research/production programs that were not banned by the 1925 convention. It was thought that parties would agree to the biological conventions well in advance of ironing out differences on chemical stockpiles.¹⁰⁵ These efforts resulted in the 1972 Biological and Toxic Weapons Convention.

Article I of this convention states:

Each State Party to this Convention undertakes never in any circumstances to develop, produce, stockpile or otherwise acquire or retain: 1) Microbial or other biological agents, or toxins whatever their origin or method of production, of types and quantities that have no justification for prophylactic, protective, or other peaceful purposes; and 2) Weapons, equipment or means of delivery designed to use such agents or toxins for hostile purposes or in armed conflict.¹⁰⁶

At first glance, this seems like a fairly broad ban applying to the hypothetical threat system; however, upon deeper examination, a few shortcomings are noted. The preamble and additional articles continually use the words “bacteriological” and “toxin” to reinforce what is banned. Use of the term bacteriological also reinforces the same term used in the 1925 Geneva Convention. The word toxin is defined to be a substance “falling between biologicals and chemicals in that they act like chemicals but are ordinarily produced by biological or microbic processes.”¹⁰⁷ This language does not appear to cover the aforementioned potential application of artificial chromosome insertion of modified genes that could affect apoptosis or HER pathway regulatory processes—no infectious bacteria, virus, or toxin (as defined by the convention) is involved. Is this semantics or a legitimate case of novel discoveries presenting scenarios that could not have been considered when the conventions were formed? One must also consider Germany’s first use of asphyxiating gas in WWI. Though apparently banned by the 1899 and 1907 Hague conventions that prohibited asphyxiating gases *delivered by projectiles*, Germany claimed they were not in technical violation as they delivered it by releasing it from containers on the ground when wind conditions were favorable.¹⁰⁸ It would be prudent to address any emerging loopholes in the 1972 BWC Convention.

While genetic research holds the promise of advanced vaccines, treatment of disease, and repair of damaged cell structures; the same knowledge has a dual-use dark side in that it could be applied to selectively target crops, individuals, and groups of people with genetic pathogens.¹⁰⁹ The BWC convention permits peaceful research which, given the potential dual-use nature of genetic research, may take you right to the point of actual weaponization, leaving little time for inspection regimes to uncover any violations or for a response to nations exercising their article XIII right to withdraw: “each party to this convention shall in exercising its national sovereignty have the right to withdraw from the Convention if it decides that extraordinary events, related to the subject matter of the Convention, have jeopardized the supreme interests of its country.”¹¹⁰ It is imperative to note that the People’s Republic of China has not signed this important convention, using the rationale that it is a sham since it does not include chemical weapons.¹¹¹

Even if treaties banning such weapons applied, non-proliferation in this area is problematic. Former Soviet biowarfare leader Ken Alibek concisely describes the non-proliferation challenge: “If somebody decides to develop biological weapons, you’re not going to detect it...maybe our only response is defense...all the information you need you can get from the scientific journals...much genetic weapon research can pass as legitimate research.”¹¹² When the World Health Organization was preparing to eradicate smallpox, Alibek’s team sequenced the virus’s genes for future studies...the work was legal and open, but conducted for the true purpose of engineering chimera viruses that could evade vaccines or treatments.¹¹³

Other investigators support that the existing conventions are unsatisfactory. The British Medical Association published a 21 January 1999 report stating that the Biological and Toxin Weapons Convention of 1972 needs urgent strengthening. In “Next Generation Bioweapons,” Ainscough summarizes the historical ineffectiveness of the 1972 BWC:

Several signatories of the 1972 BWC, including Iraq and the former Soviet Union, have participated in activities outlawed by the convention. These events demonstrate the ineffectiveness of the convention as the sole means for eradicating biological weapons and preventing further proliferation. Ultimately, the most effective deterrent to their use has turned out to be the fear of retaliation. During the Gulf War, it is believed that Iraq was deterred from using biologicals and chemicals because Saddam Hussein

feared nuclear or otherwise overwhelming retaliation. We cannot be sure that future enemies will be so intimidated. Certainly, non-state terrorist actors will not be deterred as easily. Biotechnology has made it possible to inflict mass casualties using only small scale special operations that can evade detection in attempt to avoid retribution. In asymmetric warfare, biological weapons are seen as a “great equalizer.”¹¹⁴

To Ainscough’s conclusion we can add that pairing genetic weapons with MAVs and DNA detectors may be precise enough to argue that these are not terror weapons at all, hence increasing the potential for future use. This potential may be reinforced by considering whether self-defense doctrines permit the envisioned threat system.

Self-defense doctrines typically include necessity, imminent threat, reasonably available information, lawful purpose, and proportionality.¹¹⁵ With a published and operational U.S. national security strategy justifying at least pre-emptive war doctrine and potentially (as seen by others) a preventive war doctrine, it is not unreasonable to expect potential adversaries to perceive a more *imminent* threat to their own security. Unable to match conventional power, they may see the *necessity* for an asymmetric response. Precision effects made possible by synergistic application of MAV and genetic weapon technology would allow *proportional* responses—in their minds, the paradigm that these are terror weapons with no military utility may no longer hold true.

As the Missile Technology Control Regime (MTCR) has been determined to apply to larger UAVs such as Global Hawk, it is worth considering what might apply to restricting MAV technology. The MTCR is an “informal political arrangement to control the proliferation of rocket and unmanned air vehicle systems capable of delivering weapons of mass destruction and their associated equipment and technology.”¹¹⁶ The increasing payloads, ranges, and weaponization of UAVs are leading to assessments of whether they are subject to this control regime. For example, the category I annex of controlled technologies applies to complete rocket and unmanned air vehicles systems capable of delivering a payload of at least 500kg to a range of at least 300km.¹¹⁷ Equipment subject to the controls tends towards reentry vehicles, boosters, cruise missiles, large UAVs, and the equipment needed to manufacture, support, and operate them. The majority of technologies described for the hypothetical threat system in this paper would not be subject to the MTCR in its current form. Precision navigation may be the only restricted area;

however, commercial technologies and swarm delivery methods would be sufficient to get systems close enough for a hand off to onboard sensors. Finally, several discussion fora on ethics in genetic research, including the Department of Energy's Genome Project web-site, omit the topic of genetic weapons, choosing instead to focus on ethical issues of privacy rights, human test subjects, and designing traits in future generations.¹¹⁸

Deterrence and Defense/Consequence Management

As Ainscough alluded, non-proliferation should not be our only policy option—deterrence should also be considered. One can look to nuclear deterrence theory for foundational concepts, though much of it is not likely to apply directly in practice. Counterforce doctrines are unlikely. The small size of these weapons and potential delivery methods (one example being plain shipping containers of virtually any size) would preclude the existence of a sizable signature that could be targeted by other means. Countervalue doctrines may also be ineffective since the country of origin may not be initially obvious. If extended forensic and investigative effort is required to determine country of origin, will the contest have already been decided?

Assuming non-proliferation and deterrence are unsuccessful, defense is also problematic. Economics do not favor the defense in this scenario. The cost ratio to defend against the V-1 in WWII was almost 4 to 1.¹¹⁹ Though smaller, the V-1 was similar in scale to manned aircraft. In a MAV scenario, we would be looking at how to defend against a delivery mechanism several orders of magnitude smaller. Even if they had a measurable radar cross-section, increasing surveillance radar sensitivity in order to detect MAVs would result in overwhelming clutter. Even if detected, engaging high numbers of small MAVs is challenging. Because it would presumably take some measure of time for a genetic weapon to achieve its intended effect, the only effective response may be to develop a rapid assessment and antidote capability.

Response Summary

Sole reliance on existing bans is insufficient, as there are emerging loopholes in the face of novel technologies, and the historical record of nonproliferation conventions contains mixed results. The BWC should be strengthened, but U.S. policy options should also include a deterrence component. The particular form of this deterrence component requires careful thought. Counterforce doctrines are largely inapplicable, and

countervalue strategies may be difficult to implement if the country or party of origin is unclear or non-deterrable. Defending against swarms of such small systems is also problematic. A very comprehensive approach involving experts from many functional disciplines is required to formulate this approach.

V. Conclusions and Recommendations

This paper began with the premise that technology trends in multiple disciplines may enable feasible low-cost, very small (inch or less) MAVs carrying powerful and precise genetic weapons within 20 years, with the ability to create precision effects that may challenge existing paradigms that ban existing biological weapons. Adversaries looking to asymmetrically counter conventionally powerful nations may work within loopholes of existing international conventions, outside of them, or withdraw from them entirely. Counter-proliferation of these technologies will be problematic, as will defending against the envisioned threat, thus creating significant potential for technological surprise that may fundamentally shift current constructs of national power and who possesses such power—at a fraction of the budget required to create and sustain large conventional forces.

The basic science for key enabling technologies has already been demonstrated. Applied research and system demonstration of potential platforms and payloads are underway in response to other requirements such as “around the corner” reconnaissance and novel medical diagnosis and treatment. Advancement of the enabling technologies is accelerating in response to these requirements and other industrial demand. Projected timelines for key enabling technologies are listed in Table 8.1. There are multiple competing paths for many of the enabling technologies that also increase the likelihood of success. The dual-use nature of these enabling technologies and the potential for moral claims to genomic research for the benefit of all nations are likely to make these enabling technologies available to potential adversaries sooner than we might otherwise expect. The totality of these observations provides strong support for the premise of this paper, which justifies beginning to plan potential responses.

Enabling Technology	Availability Timeline (Projected—P; Actual—A)
Map Human Genome	2003 (A)
Mechanical Flying Insect	Characterize Insect Flt Dynamics—1998(A) Demonstrate sufficient lift forces—2003(A) Lift-off (off board battery)—2004 (P) Indoor Autonomous Controlled Flt—2006(P) (w/onboard batt, sensors, nav electronics) Commercially Available—2012 (P)
DNA Detection Chip	Prototype—2003 (A) “Practical Applications—2005(P)
Microneedles	Prototype—2003(A) Devices “on the Market”—2008(P)
Artificial Chromosomes	Prototype—1997(A)
Cancer Cell “Self-Destruct” Code	Proteins Bak and Bax determined to disrupt mitochondria & trigger apoptosis—2001 (A)

Table 8.1 Key Enabling Technology Availability

The principal recommendation of this paper is for Northern Command (NORTHCOM) to engage the Joint Staff and Department of Homeland Security representatives to the National Security Council (NSC)’s functional Policy Coordination Committee on Proliferation, Counterproliferation, and Homeland Defense and begin a dialog in that committee on responses to this potentially emerging threat. Due to its role in Homeland Security, NORTHCOM is aptly suited to work across the many military, government agency, and private sector participants that should be involved in these discussions. The Defense Science Board should be tasked to support this activity through an independent verification of the technical feasibility of MAVs carrying genetic weapons and to assist arranging appropriate scientific community participation in response planning. Initial recommendations for this NSC policy committee to consider are:

1. Protect DNA databases as a matter of national security, not just personal privacy.

2. Consider championing granting of patents to genomic research in order to provide some measure of additional counter-proliferation protection.

3. Seek to strengthen the biological weapons ban treaty to specifically ban the development, production, fielding and use of genetic weapons, including direct injection and artificial chromosome delivery methods that do not require the use of infectious vectors.

4. Deliberately include the need to prevent using genomic information for weapons research in ethics materials related to genetic research. Work with the international medical community to create and administer appropriate oaths to genetic researchers.

5. Place DNA detection technology under export control procedures.

6. Institutionalize a “red team” process to look across the broad spectrum of emerging technologies to predict where interaction among them presents paradigm-changing asymmetric opportunities for potential adversaries. Today, what “red teaming” is done tends to focus on advances to existing systems, or is stove-piped within a technology area. Use the red team to independently assess the veracity of claims made in this paper with panels of experts in related disciplines.

7. Task DARPA to investigate potential defenses against the envisioned threat, such as evaluating the effectiveness of Radio Frequency (RF) weapons engaging swarms of prototype MAVs or Berkeley’s mechanical flying insect (MFI) and assessing the potential effectiveness of existing chemical/biological protective gear against microneedles. Investigate novel concepts such as equipping forces with “bug zappers” that attract, trap, and destroy MFIs.

The descriptions and research status of the enabling technologies described in this paper are completely available in open source material—Pandora’s Box is opened wide. Given the potential for technological surprise and the difficulty in defending against MAVs carrying genetic weapons, it is not too early to begin considering ways to prevent the need to do so. The recommendations made here are by no means exhaustive but represent a reasonable point of departure to begin formulating a response. As strategy consultant Peter Schwartz observes, “almost every time we get the future wrong, it’s not because we didn’t have good information...it’s because we didn’t want to see the answer.”¹²⁰ Regarding the scenario presented here, we should see it coming and make sure we’re wrong.

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